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14. ABSTRACT
The effort under this grant was designed to further the goals of both NASA and the Air Force in the area of small satellites in two ways: hardware development for nanosatellites, and the education of future aerospace professionals. The hardware component of the effort involved the design, construction and testing of a flight-ready nanosatellite to demonstrate several novel technologies for small satellites. The five on-board experiments, the details of which are given below, had as their emphasis the use of hardware that is capable of performing several distinct satellite functions, or is based on commercial off-the-shelf (COTS) technologies, or both. Multi-functionality and COTS systems are key to the development of low-mass, low-volume, low-cost nanosatellites. The educational component of the grant involved teams of aerospace engineering, electrical engineering and computer science undergraduates designing, developing and testing BEARSat, as well as individual graduate students, two of whom serve in

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Nanosatellite Demonstration of Multi-Functional Space Systems:
A Grant under Air Force University Nanosat Program-4

Grant Number FA9550-05-1-0386
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Final Report

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Objectives

The objective of the effort under this grant was the design, construction and testing of a flight-ready nanosatellite, named the *Bantamweight Energy Augmentation Research Satellite*, or *BEARSat*. This spacecraft was designed to demonstrate several novel technologies that hold promise for the growing field of small satellites. The majority of the experimental systems that were developed were either multi-functional hardware or commercial off-the-shelf systems, both of which are highly desirable for nanosatellite applications: in the former case to reduce mass, in the second to reduce cost.

The specific experimental systems that were developed and tested under this project were: two passive thermal control systems based on the use of phase-change material; a reaction wheel attitude control system, designed and built in-house by the student team; and a low-profile refractive solar array concentrator, again designed and built in-house. In addition, an experiment to test radiation-induced single event upsets in commercial off-the-shelf flash memory components was developed. It can be noted that two of these systems are associated with the thermal control of the satellite. This is a result of the fact that nanosatellites fly in low-Earth orbit, with frequent cycling from day to night. This cycling typically causes larger temperature swings for a small satellite than for a larger vehicle. Thermal control of nanosatellites is therefore a challenging problem, and novel technologies to address it are of benefit.

The educational component of this project was also of great importance. As part of this effort, teams of aerospace engineering, electrical engineering and computer science students, at both the undergraduate and graduate levels, were heavily involved in the nanosatellite project: they carried out analysis, design, construction and testing of the spacecraft. This experience has given them a comprehensive exposure to real spaceflight design issues, making them attractive to potential employers such as the Air Force, NASA, the Navy and industry. Indeed, a substantial fraction of the students who were involved in the project are now employed on spacecraft

projects. In this way, the project has helped to address the critical national need for new highly qualified aerospace engineers.

Report of Effort under Grant

Background

Miniaturization continues to increase the functionality of small spacecraft, and most notably nanosatellites, considerably over what was possible in the past. This leads to the very attractive concept of using a number of smaller satellites, orbiting together and operating cooperatively, to carry out a specified mission. Such *satellite formations*, or *swarms* (see, for instance, Refs. 1-5) promise space operations at greatly reduced cost, and possess a highly desirable "graceful degradation" property: loss of any one satellite does not jeopardize the entire mission.

The effort under this grant was designed to further the goals of both NASA and the Air Force in the area of small satellites in two ways: hardware development for nanosatellites, and the education of future aerospace professionals. The hardware component of the effort involved the design, construction and testing of a flight-ready nanosatellite to demonstrate several novel technologies for small satellites. The five on-board experiments, the details of which are given below, had as their emphasis the use of hardware that is capable of performing several distinct satellite functions, or is based on commercial off-the-shelf (COTS) technologies, or both. Multi-functionality and COTS systems are key to the development of low-mass, low-volume, low-cost nanosatellites. The educational component of the grant involved teams of aerospace engineering, electrical engineering and computer science undergraduates designing, developing and testing BEARSat, as well as individual graduate students, two of whom serve in succession as Project Manager. As a result of this effort, NASA and the Air Force have additional young aerospace engineers available with practical experience in nanosatellite technology.

The BEARSat work, in both its hardware development and educational facets, built upon, and helped focus, the on-going BalloonSat program, termed *Instrumentation Carrier for Aerospace Research in the Upper Stratosphere (ICARUS)*, at the University of Cincinnati. This program, supported by the Ohio Space Grant Consortium, involves the design, construction and launch, by a team of students, of a series of nanosatellite-scale payloads to altitudes approaching 100,000 ft by weather balloon; three ICARUS launches have occurred to date since Spring 2005. In particular, the BEARSat thermal switch experiment was tested in space-like conditions on ICARUS missions and, if BEARSat had been selected for launch, additional prototype subsystems were to have been test-flown as well. The ICARUS effort in turn is based on previous sounding rocket and KC-135 experiments that have been carried out as student-based projects. Work on orbital operations plans for BEARSat also made use of the research of the Principal Investigator in the field of the formation flight of small satellites for the Air Force Research Laboratory and NASA Goddard Space Flight Center. In addition, it exploited his experience conducting orbital mechanics analysis for several small satellite flight projects: the AERCam Sprint free-flyer developed by NASA Johnson Space Center for Space Shuttle and International Space Station inspection tasks, and the Surrey Satellite Technology, Ltd. UoSAT-12 minisatellite and SNAP-1 nanosatellite. Finally, the effort made use of the great expertise of

the partner organizations: L-3 Cincinnati (formerly CMC Electronics Cincinnati), with extensive experience in the development of communications systems for launch vehicles and spacecraft (including the Mars Exploration Rovers), and NASA Glenn Research Center, with expertise in spacecraft power systems.

Details will now be given of the BEARSat nanosatellite, including the changes that had to be made to the originally proposed design over the course of the grant, and the reasons behind these modifications. Following this, a discussion will be given of the educational component of the grant.

BEARSat Nanosatellite Design

The BEARSat nanosatellite as originally proposed was to be a cube-shaped spacecraft, 0.4 m on a side, and with a total mass of 27 kg: see Figure 1. The spacecraft structure was to be constructed of graphite epoxy, and blanketed with solar cells (apart from the face upon which the launch attach ring is mounted). The attitude control system was to be capable of three-axis stabilization.

Significant changes to the overall proposed design were made over the course of the grant as a result of information in the *University Nanosat-4 Program User's Guide*, as well as in response to feedback from Air Force personnel. Firstly, the structure dimensions have been modified to simultaneously reflect the new launch envelope dimensions and accommodate the LightBand separation system footprint: see Figure 2 for the final structural design, as reflected in the constructed satellite (Figures 3 and 4). Secondly, the graphite epoxy structure has been replaced by one of aluminum, as part of the general prohibition on using composites in primary structure, in order to avoid the risk of outgassing. Another important consideration was that, in order to withstand launch vibrations with an acceptable safety factor, the University Nanosat Program User's Guide stipulates that the lowest natural frequency of the satellite be at least 100 Hz. This constraint drove many aspects of the spacecraft structure that can be seen in Figure 2, along with the boxes that contain the various electronics systems (communications, computing and data handling, and power supply and regulation), as well as the reaction wheel. Since these boxes are the most massive components in the spacecraft design, their positioning strongly affects the mass properties of the satellite: their locations were selected so as to give moments of inertia that prevent the spacecraft from settling into a spin about the bottom face. As this face is the only one not extensively covered in solar cells, this design feature prevents BEARSat going into an uncommanded spin with no solar cells facing towards the Sun for an extended period, so draining the batteries: it is therefore a safety feature in the very unlikely event of an uncommanded spin. (A major axis spin of this form led to the loss of the Lewis spacecraft three days after launch, and the loss of operational capability of the Soho solar observer for three months.)

In addition, Air Force Research Laboratory/VS personnel emphasized to us that we should make our spacecraft able to tolerate launch into a wide range of orbits, increasing the likelihood of identifying a secondary launch opportunity for it. This has many implications for the design: for instance, thermal conditions in *geosynchronous transfer orbit* (GTO) can be challenging, while communications in either GTO (due to the extended range) or a low equatorial orbit (due to

ground station visibility) can be difficult. However, the team was able to overcome them successfully.

The experimental systems as originally proposed to be flown (with details given shortly), are indicated in Figure 1 as follows:

(1) Phase Change Material Reservoir (PCMR): green box on middle equipment shelf
(2) Phase Change Material Switch (PCMS): red cylinder on middle equipment shelf
(3) Multifunction Spacecraft Flywheel for Nanosatellites (MSFN): grey cylinder on upper shelf
(4) Solar Collector/Radiator for Nanosatellites (SCRN): silvered external angled surfaces
(5) Electronics Radiation Susceptibility Testbed (ERST): yellow box on upper equipment shelf

The nanosatellite is also equipped with support systems, including: magnetorquers (shown in Figure 1 as the three black orthogonal rods; these were designed and built in-house by the student team in the final design); three-axis magnetometer (purple box at upper corner of spacecraft); sun sensors (gold rectangles on upper corners of satellite); GPS receiver (one patch antenna visible as pale blue square on top face; deleted from the final design); NiCd batteries (shown as brown box below middle equipment shelf); and a VHF communications system, on-board processor and associated solid state memory (all included in the central module depicted as grey box on middle equipment shelf). Partners in the BEARSat program included L-3 Cincinnati (formerly CMC Electronics Cincinnati), with extensive experience in the development of communications systems for launch vehicles and spacecraft, including the Mars Exploration Rovers, and NASA Glenn Research Center, with expertise in spacecraft power systems.

The motivation for, and technical description of, each of the experimental systems will now be given in detail, together with a description of the modifications that occurred to several of these over the course pf the project, together with the reasons.

(1) PCMR: The thermal environment in low-Earth orbit poses a particularly severe test for nanosatellites for several different reasons. The first factor is that such spacecraft do not provide sufficient volume to thermally isolate sensitive internal components from the outer surface of the satellite. Their small volume and mass likewise prevent the use of bulky thermal control component designs that have been developed for larger spacecraft. In addition, launch opportunities for nanosatellites arise only as secondary payloads, into orbits that are optimized for the requirements of the primary payload. Consequently, the final orbit may be suboptimal from the point of view of the nanosatellite, leading to thermal environment problems related to, for instance, the solar beta angle and/or day-to-night cycles.

Another factor rendering nanosatellites particularly susceptible to thermal problems is their small heat capacity. This can be shown by a simple parametric analysis in terms of the linear dimension, L, of a satellite: the satellite mass (being proportional to volume) then satisfies $m \propto L^3$, and solar heat input (proportional to surface area) satisfies $Q_{in} \propto L^2$. Consequently, the rate at which spacecraft temperature changes is of the form $\dot{T} = Q_{net}/mc \propto L^{-1}$, where c is the mean specific heat capacity of the satellite. Hence, the rate at which the spacecraft temperature changes is inversely proportional to satellite linear dimension, and so can be considerable for nanosatellites. This makes thermal control of such small vehicles

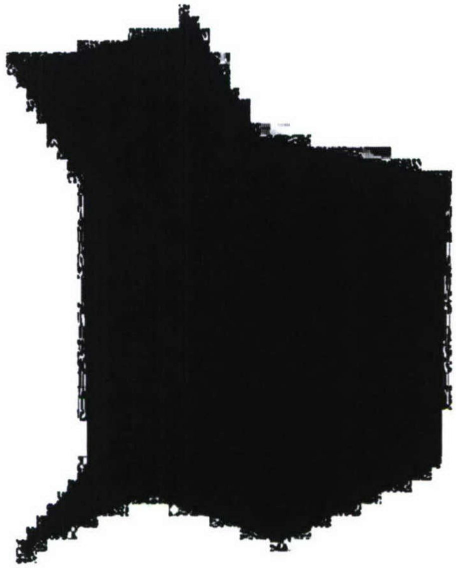

Fig. 1 BEARSat Configuration as Initially Proposed

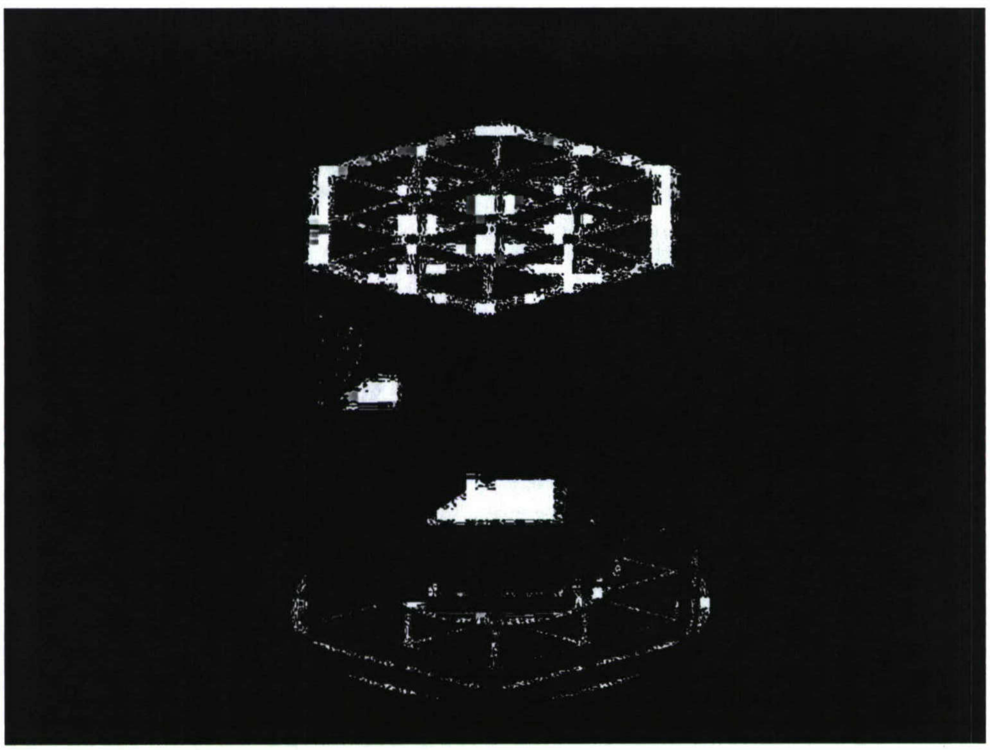

Fig. 2 Final BEARSat Configuration

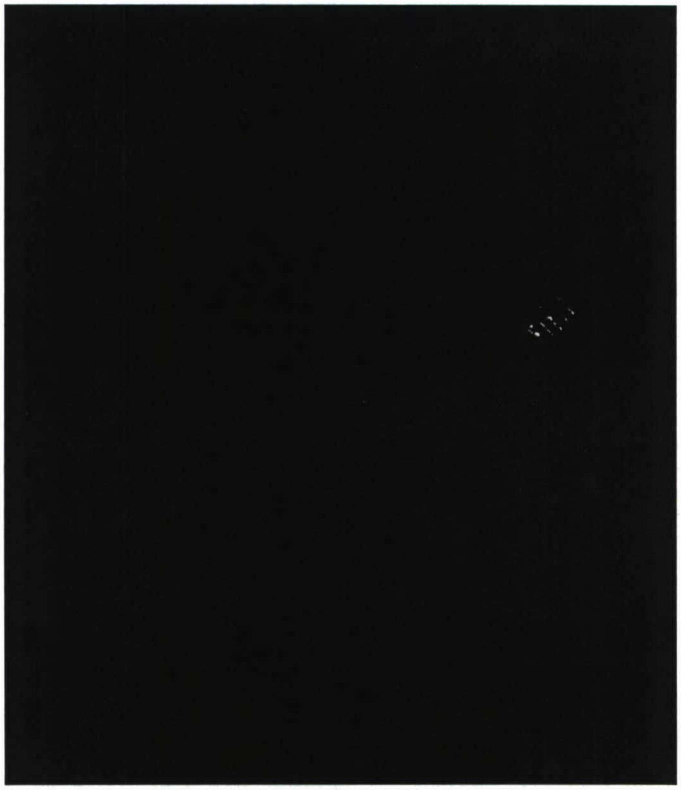

Fig. 3 BEARSat Spacecraft

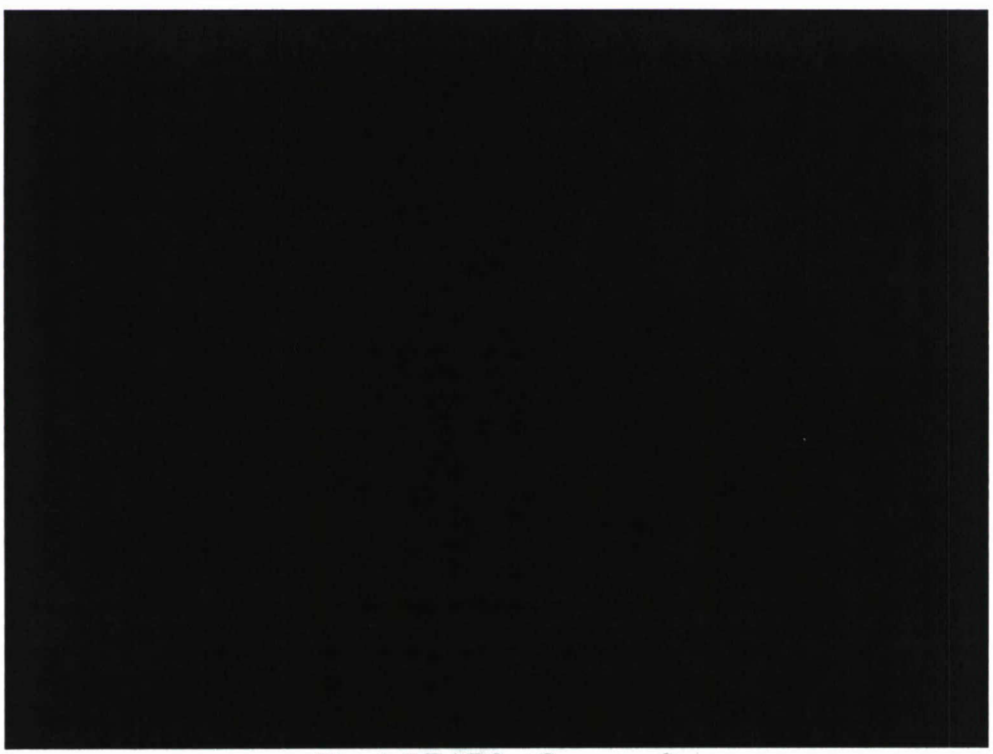

Fig. 4 BEARSat Spacecraft

particularly challenging. It is for this reason that two of the BEARSat experiments were devoted to thermal control.

The PCMR is a purely passive, multi-functional solution to the problem of maintaining the internal systems of a nanosatellite within their specified temperature range under all environmental conditions. The main component is a reservoir of *phase change material (PCM)*, paraffin in the case of BEARSat, in thermal contact with the internal spacecraft systems by being attached to them via a coldplate. In normal nanosatellite operations, the PCM is in its liquid state; however, it freezes if the systems run cold, so liberating a considerable amount of energy (its latent heat of fusion). Using such a system, the absorptivity and emissivity of the exterior surface coatings of the nanosatellite can be selected so as give an acceptable equilibrium temperature on the day side of the orbit, with all systems operating nominally. The cold case (orbital night and/or certain systems deactivated) is then dealt with by means of the freezing of the PCM, with no need for active thermal control system components. In the final spacecraft design, the PCMR was mounted, in two separate containers, on the sides of the communications box: this system is one of the highest power consumers, and hence waste heat generators, in the entire nanosatellite. The reservoirs were broken into several distinct chambers, and great care was taken to avoid leakage once the PCMR was charged with paraffin before launch, by means of O-ring seals.

(2) PCMS: The PCMS is an alternative approach to the problem of controlling the temperature of nanosatellite internal components under varying environmental conditions. The PCMS is based on the use of phase-change material, as was the PCMR, and is again a purely passive system, but the principle of operation is entirely different. In this case, the PCM physical property that is exploited is not the latent heat of fusion, but rather the increase in volume of the PCM upon melting: for the material used in the PCMS, again paraffin, this volumetric increase is approximately 15%. The central component of the PCMS, shown as the small red cylinder to the side of the main electronics box on the middle equipment shelf in Figure 1, is a piston filled with paraffin wax. If the temperature of the electronics box and battery packs increases sufficiently to melt the PCM, the expansion of the melting wax causes the piston to extend. This in turn pulls one end of a flexible metal strip so as to contact a small metal plate that is mounted to the inside of the spacecraft sidewall. This flexible strip, the other end of which is mounted to the electronics box/battery pack, then forms a good thermal conduction path to the outer spacecraft shell, where the waste heat is radiated to space. Conversely, when the electronics temperature decreases, the paraffin resolidifies, and so shrinks. The spring-loaded piston then returns to its original length, so severing the conduction path and causing the electronics/batteries to retain their heat. A great deal of design work went into the PCMS, leading to several distinct prototype designs that were tested in both ICARUS and SHOT balloon flights and in thermal chamber tests at L-3. Key design considerations were minimization of total mass and volume, ease of filling with paraffin before launch, and prevention of leakage.

(3) MSFN: Spacecraft commonly make use sets of wheels spinning at high angular rates for attitude control: these are either *reaction wheels*, with fixed axes but variable speeds, or *control moment gyroscopes (CMGs)*, with constant spin rates but gimbaled axis of rotation. Attitude control wheels exchange angular momentum with the spacecraft body, so producing the body rates that are required in order to perform any specified maneuver. A major advantage of attitude control based on wheels is that no expendables are required; only electrical power, to operate the wheel drive motor, is used. A particularly attractive wheel-based control scheme for nanosatellites is the *momentum bias* approach, wherein the single reaction wheel has spin axis aligned with the orbit normal. The angular momentum of the wheel then keeps the spacecraft aligned with this inertially fixed direction, and small changes in wheel speed can be used to rotate the satellite so to remain Earth-facing.

Attitude control wheels are necessarily capable of storing a significant amount of rotational kinetic energy. They could therefore in principle be used as energy storage/retrieval devices, in a similar fashion to terrestrial flywheels, instead of massive (and lifetime-limited) batteries. If a spacecraft were equipped with a pair of identical counter-rotating flywheels, this system would provide both attitude control and energy storage. For instance, increasing the spin rate of both wheels by the same amount increases the total energy stored without changing the net angular momentum, and so without affecting the attitude of the vehicle. Conversely, increasing the spin rate of one wheel while slowing the other by an equal amount changes the net angular momentum, so causing the spacecraft to rotate, without altering the total amount of energy stored. Flywheels have been actively investigated by NASA Glenn Research Center for applications to large spacecraft such as the International Space Station, but no flight opportunities for the technology have yet arisen.

The MSFN as originally proposed was to be a demonstration of a miniaturized flywheel system for combined attitude control and energy storage, suited for applications to nanosatellites. The system would include two flywheels, rotating about the same axis but in opposite directions, with independent drive motors. Both wheels are enclosed in the same cylindrical housing, shown as the silver cylinder on the upper equipment shelf in Figure 1. Sizing of these wheels is based on both attitude control and energy storage considerations: the key parameters are rotational kinetic energy at a given spin rate (energy storage design parameter), and angular momentum at this spin rate (attitude control design parameter). These quantities can be found in terms of the moment of inertia of each wheel: if wheel radius is r, and most of the mass m is concentrated in a rim of thickness t and height h, the moment of inertia is given as $I = mr^2$, where $m = 2\pi\rho rth$ for a wheel material of density ρ. The stored rotational kinetic energy at spin rate ω is then $T = \frac{1}{2}I\omega^2 = \pi\rho r^3 th\omega^2$: this can be considerable for either a large wheel or a small, high-speed one. The corresponding wheel angular momentum is $H = I\omega = 2\pi\rho r^3 th\omega$, and the torque that is exerted on the spacecraft when the wheel experiences an angular acceleration α is $\tau = I\alpha = 2\pi\rho r^3 th\alpha$.

As a result of feedback from Air Force/VS program personnel at the Preliminary Design Review, it was decided to remove the MSFN experiment from the spacecraft: although energy storage using flywheels is interesting and potentially useful, the risks involved with this experiment, and its ramifications for other spacecraft systems (notably power), were judged to be excessive for a project at this budget level.

(4) *SCRN:* One fundamental limitation of nanosatellites is the electrical power that can be generated by body-mounted solar arrays. This is a direct consequence of the small size of such spacecraft: if a nanosatellite has linear dimension L as before, the power generated is proportional to L^2. Nanosatellites are therefore typically power-limited spacecraft. For the example of the proposed spacecraft, each face (entirely covered with solar cells of 20% efficiency) generates a power of at most 44 W.

The SCRN to be tested on the proposed nanosatellite is a simple, low mass system to overcome this limitation. It consists of two surfaces of metalized Teflon supported by a rigid framework. Initially, these surfaces are held flat against one face of the spacecraft by a single latch; after launch and initial checkout, this latch is released, for instance by a PCM-based actuator, and the spring-loaded SCRN surfaces deploy to an angle of 45 deg relative to the spacecraft sides (see Fig. 1). In this position, the surfaces serve as solar collectors, reflecting light onto the solar arrays on the adjacent satellite faces. This increased illumination will in turn lead to increased power generation from these arrays. Note that a similar power augmentation technique has been demonstrated on certain late-model Boeing geosynchronous communication satellites. This showed that the basic approach does indeed work, although eventual degradation of the solar collector reflectivity on those spacecraft reduced the long-term benefits.

The SCRN is much simpler, and has a much lower mass, than other more conventional power augmentation solutions such as the addition of deployable solar arrays. In fact, the mass of the SCRN in the current design is less than 0.1 kg per flap (5 mil Teflon is assumed). It also has the desirable property of being multi-functional: not only are the side booms used as the antennas for the spacecraft VHF radio system, but the flaps themselves also serve as spacecraft thermal radiators. Two possible flap surfaces have both been shown to be well suited to radiator applications. If the SCRN is constructed of silvered Teflon, it has solar absorptivity 0.08 and IR emissivity 0.66: this high ε/α ratio makes it well suited for use as a radiator surface, with a full-Sun equilibrium temperature of approximately –39 C (234 K). If the SCRN is instead constructed of aluminized Teflon, its solar absorptivity is 0.16 and IR emissivity 0.80: the full-Sun equilibrium temperature is now somewhat increased to –6 C (267 K), but is still low enough to make a very acceptable radiator surface. The SCRN metallic support frame serves as a strong thermal conduction path from the spacecraft structure to the Teflon radiator surfaces: when the PCMS thermal switch closes, this is the path taken by the heat that is output by the internal nanosatellite systems.

The solar arrays on five of the faces of the nanosatellite (all except the face upon which the launch attach ring is mounted) are identical. The illumination onto one of these faces is augmented by both SCRN panels, one face is augmented by a single SCRN panel, and three are unaugmented. The power improvement produced by the SCRN can therefore be quantified by conducting the following test: rotate the spacecraft so as to make each face broadside to the Sun in turn, and determine the power generated by measuring array current and voltages. Comparing the two-SCRN, one-SCRN and unaugmented array power levels then demonstrates the improvement produced by the SCRN. In addition, the function of its

support booms as the spacecraft VHF antennas will be quantified by the measured received signal strength on the ground, and the function of the SCRN as a thermal radiator by means of spacecraft temperature data.

Following discussions with Air Force personnel at the Critical Design Review, the Solar Collector/Radiator for Nanosatellites (SCRN), a reflective surface intended to increase the solar illumination on certain of the spacecraft solar cells, was modified, reducing its area so as to allow it be launched already in its final position, rather than deployed on-orbit: this eliminated a deployment mechanism and the associated risks. A subsequent further design modification, motivated by the work of one of the aerospace student team members, replaced the original reflective SCRN by a refractive approach, using a prism to increase the solar illumination on the solar arrays under a range of lighting angles. This modification further reduced the required SCRN area while still providing adequate solar concentration for the purposes of a flight demonstration.

(5) ERST: The low costs desired for small spacecraft, and in particular nanosatellites, make the use of commercial off-the-shelf components a highly attractive option. However, the space environment raises challenges that can make the successful use of such technologies problematical: a precise knowledge of these challenges, and how to overcome them, is therefore necessary. Low-Earth orbit, where most nanosatellite missions are proposed to occur, is a particularly difficult environment. One difficulty is the frequent day-night cycling that occurs as the satellite orbits the Earth: these cycles, typically around 16 per day or 5000 per year, produce severe thermal cycling and battery lifetime issues. The thermal issues are addressed by the PCMR, PCMS and SCRN experiments, while the MSFN experiment, with its potential to reduce dependence on batteries, is linked to the lifetime issue.

The ERTS experiment (shown as the yellow box on the upper equipment shelf in Fig. 1) addresses another of the severe environmental concerns in low-Earth orbit, namely radiation. The high-energy protons that are trapped in the radiation belts of the Earth can cause data or programs in on-board computer memory devices to become corrupted by *single-event upsets (SEUs)*: if undetected, this can clearly be a serious problem for spacecraft operations. High-energy protons can be particularly severe at the high latitude regions that are flown through by the very many spacecraft that are in polar or Sun-synchronous orbits.

The ERTS package consists of several COTS flash memory cards, with known initial patterns of stored data. In flight, these cards would be read periodically by the on-board computer, and any changes from the initial pattern detected. The resulting evidence for SEUs would then be transmitted to the ground. This would allow the relative performance of the several alternative COTS systems to be quantified, leading to conclusions as to the preferred option for future space applications. In addition, correlation of SEU activity with spacecraft location around the Earth would also be achievable, demonstrating the effects of latitude and such radiation disruptions as the South Atlantic Anomaly.

A large part of the BEARSat design effort has inevitably gone into hardware development, either for components to be developed in-house, or for components obtained from external vendors.

For instance, several prototype versions of the PCMS experiment, in its final configuration a metallic piston, were constructed at the University, as was the reaction wheel and several magnetic torquers for the generation of attitude control torques. Circuit boards for all electronic systems were laid out at the University, and then sent out for fabrication. Thermal testing of hardware components developed in-house was carried out at our industrial partner, L-3 (formerly CMC Cincinnati Electronics).

In addition to this hardware-related design work, a great deal of effort went into the development of BEARSat operations modes (both nominal and contingency), including the initial detumble and commissioning phase of the mission, the nominal data-collection phase, the final safing and decommissioning phase, and recovery from a loss of either power, attitude control or communications contact with the ground. As part of this work, careful consideration went into the desired nominal attitude profile of the satellite and ways of achieving this: this led not only to a refinement of the sensor and actuator hardware required for the spacecraft, but also an improved understanding of the required on-board attitude control algorithms. Development of these operational modes was made more challenging by the fact that, as previously discussed, the spacecraft was designed to be operable in many possible orbits. An additional aspect of this work was the development of extensive project documentation. This documentation proved to be very useful for bringing new team members up to date on past project work.

In addition, facilities at the university had to be found that could support the various facets of the BEARSat project. Specifically, laboratory space for mechanical fabrication was identified and moved into, as was an electronics construction room, a secure storage facility for flight hardware, a cleanroom, and a ground station for commanding the spacecraft and receiving downlinked data from it.

Relevance to AFRL and NASA Programs

Numerous AFRL and NASA missions are currently under development or proposed that make use of formation flight of small satellites, and so can be aided by the proposed research effort. Distributed spacecraft techniques allow some of these scientific investigations to be carried out more efficiently, and with greater flexibility, that would be the case with a single spacecraft; others require simultaneous measurements at numerous points, and so would not be possible at all without distributed spacecraft.

One example of a satellite cluster that was launched in recent years is the NASA ST5 mission, or Nanosat Constellation Trailblazer, which involves the launch of three 21.5 kg nanosatellites into Earth orbit by means of a Pegasus launch vehicle. These spacecraft demonstrated autonomous operation, e.g. cooperative sensor activation and data rate selection, and orbital maneuvering by a formation of satellites. The science measurements that was taken by the magnetometers and energetic particle detectors on-board these spacecraft allowed the effects of solar activity on the magnetosphere to be studied. This knowledge will be valuable not only for future space operations (as these solar-induced magnetosphere effects lead to transient high-altitude radiation belts), but also for Earth-based power distribution systems (as they also lead to large currents in the high-latitude ionosphere, and consequently to power grid disruptions). Another relatively near-term NASA satellite formation flight project is the Magnetospheric Multiscale (MMS)

mission: this component of the Sun-Earth Connection Program uses a cluster of four spacecraft, placed in a highly elliptical orbit, to perform simultaneous science measurements at dispersed points in the magnetosphere of the Earth. This data will assist in the understanding and prediction of space weather.

The novel technologies that were developed for BEARSat are directly applicable to any future AFRL or NASA spacecraft in the nanosatellite class. In addition, the grant has produced a set of aerospace engineering students, at both the B.S. and M.S. levels, who have direct experience of the hardware and operational issues that occur in space flight projects. The Air Force, NASA and industry benefit greatly by being able to hire newly-graduated engineers who complement their analytical skills with this type of practical experience, particularly in the emerging field of small satellites.

Educational Component of Effort

The educational aspects of the University Nanosat Program are reflected in the fact that the BEARSat project has formed the basis for material that has been added to space-related courses at the University of Cincinnati. In addition, several detailed presentations on BEARSat were given by members of the student team to underclassmen, as well to as to prospective students and their parents, generating a great deal of interest in the project, and in aerospace engineering in general.

In more detail, the BEARSat nanosatellite effort has contributed greatly to both the undergraduate and graduate programs in Aerospace Engineering, Electrical Engineering and Computer Science at the University of Cincinnati, by providing a real-world application of many of the spacecraft engineering analytical tools that the students are exposed to in several existing courses. It built upon, and formed a logical extension to, the ICARUS BalloonSat project that is currently under way: see Figures 5 and 6. The Principal Investigator has led a group of undergraduates and graduate students who have been designing, constructing and flying a series of BalloonSat payloads since 2004. These small vehicles (mass less than 6 kg), funded by the Ohio Space Grant Consortium, are carried to altitudes approaching 100,000 ft under weather balloons and then returned to the surface by parachute, with a payload consisting of a GPS receiver, an amateur radio transmitting GPS position data to the chase team via APRS, a digital camera, activated by timer circuit and storing a sequence of images on flash memory, and a flight-specific experiment, for instance a set of solar cells to be calibrated above the sensible atmosphere for NASA Glenn Research Center, or a prototype of the BEARSat thermal switch. First launch occurred in Spring 2005. The BalloonSat project in many ways formed a natural bridge to the BEARSat nanosatellite effort: it is a small vehicle that is designed to meet thermal, vacuum and launch loading conditions that are similar to those encountered for orbital missions. The ICARUS BalloonSat student group therefore formed the nucleus for the students who worked on the BEARSat project. In particular, the interdisciplinary work between aerospace and electrical engineering students that took place on the ICARUS-1 flight project formed the model for how to proceed on BEARSat.

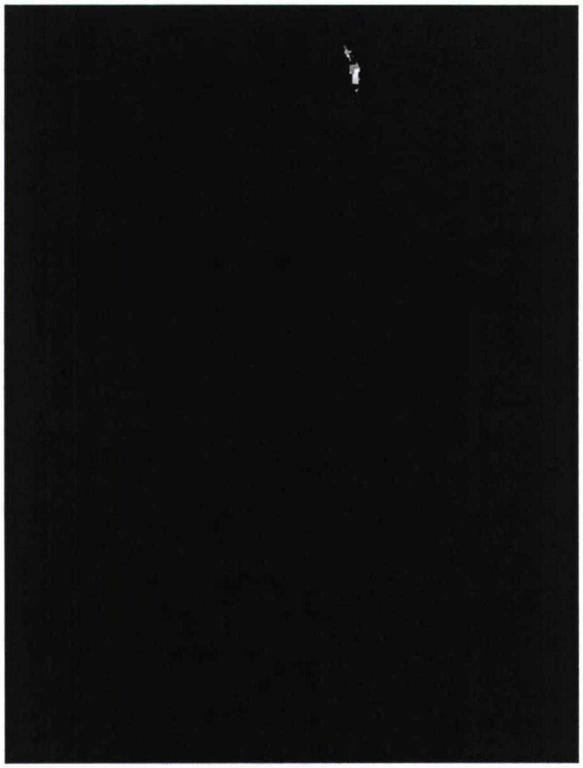

Figure 5 ICARUS-2 Launch

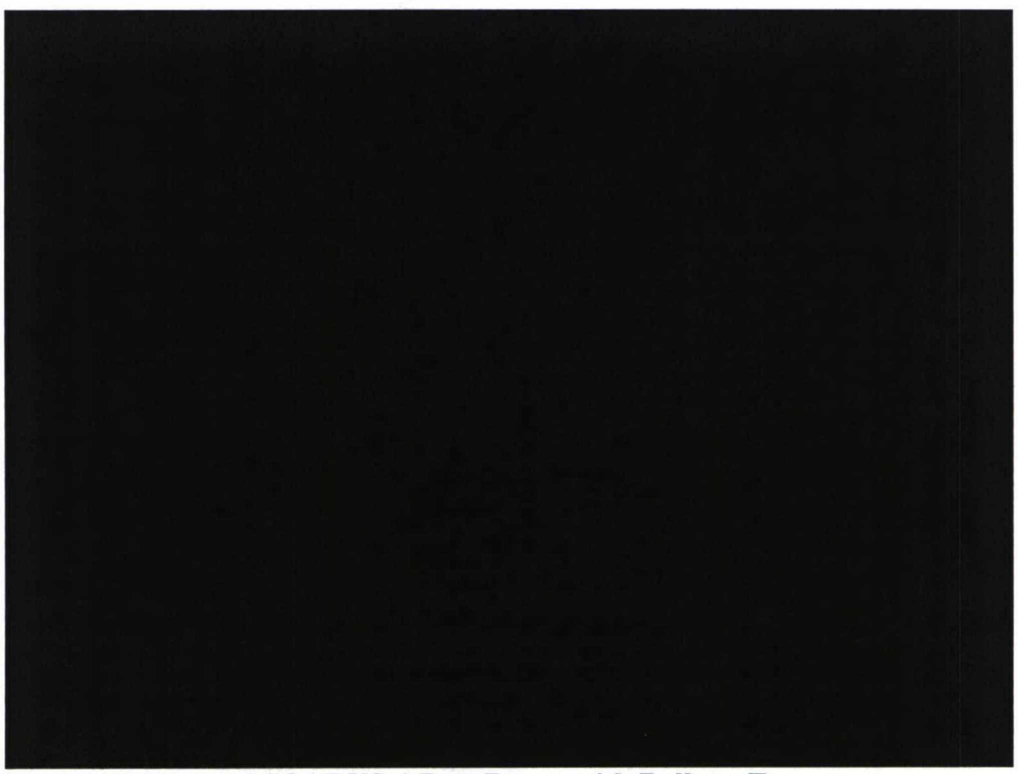

Figure 6 ICARUS-1 Post-Burst, with Balloon Fragment

Graduate student involvement in the BEARSat project was key. Notably, a succession of M.S. students took the role of Project Manager, providing guidance and mentoring to the undergraduate teams, monitoring the ordering of hardware from outside suppliers, the development of in-house components, and the testing of all systems, and liaising between the student teams and the Principal Investigator.

Personnel

Faculty
Dr. Trevor Williams, Principal Investigator
Dr. Albert Bosse
Dr. Altan Ferendici
Dr. Karen Davis

Graduate students
Eric Riedl, Project Manager (Year 1)
Jacob Hause, Project Manager (Year 2)
Matthew Urbaniak, Assistant Project Manager

Undergraduate students
A team of Aerospace Engineering undergraduates
A team of Electrical Engineering undergraduates
A team of Computer Science undergraduates

Note that certain of these students are now employed at Orbital Sciences Corporation, the Naval Research Laboratory and the Air Force Research Laboratory. In addition, certain of the students who worked on BEARSat as undergraduates have followed this by graduate work at the University of Cincinnati, The Ohio State University and Georgia Institute of Technology, largely on research into areas related to their BEARSat effort. The experience of working on BEARSat has therefore proved very useful to the team members.

Publications under Grant

None

Interactions/Transitions

Design Reviews Conducted
[1] System Concept Review, teleconference with AFRL/VS and NASA Goddard, May 2005
[2] Design Review presentation at L-3/Cincinnati Electronics, Aug. 2005
[3] Preliminary Design Review, Logan, Utah (after Small Satellite Conference), Aug. 2005
[4] Design Review teleconference with Orbital Sciences Corporation, Dulles, VA, Feb. 2006
[5] Critical Design Review, University of Cincinnati, Mar. 2006
[6] Proto-Qualification Review, Logan, Utah (at Small Satellite Conference), Aug, 2006
[7] Flight Competition Review, Albuquerque, New Mexico, Mar. 2007

New Discoveries, Inventions, or Patent Disclosures

None

Honors/Awards

[1] Trevor Williams, Master Educator Award, College of Engineering, University of Cincinnati, June 2006

[2] Trevor Williams, Recognition of Excellence, EVA Office, NASA Johnson Space Center, July 2006

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2. R. Sedwick, D. Miller and E. Kong, "Mitigation of Differential Perturbations in Clusters of Formation Flying Satellites", Proc. AAS/AIAA Space Flight Mechanics Meeting, Breckenridge, CO, Feb. 1999.
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4. T.W. Williams and Z.-S. Wang, "Uses of Solar Radiation Pressure for Satellite Formation Flight", *International Journal of Robust and Nonlinear Control*, Jan. 2002.
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8. W.J. Larson and J.R. Wertz, *Space Mission Analysis and Design*, 3rd edition, Microcosm/Kluwer, 1999.
9. J.R. Wertz, *Spacecraft Attitude Determination and Control*, 1984.
10. G.L. Slater and T.W. Williams, "Experience with an Integrated Spacecraft Engineering Course for Aerospace Engineering Students", presented at ASEE Annual Meeting, St. Louis, Missouri, July 2000.

Appendix: Flight Competition Review Presentation

BEARSat

University of Cincinnati
University Nanosat 4
FCR Presentation

March 27th, 2007
Albuquerque, NM

UNIVERSITY OF Cincinnati

Mission Overview

Mission Statement

The purpose of the University of Cincinnati's BEARSat is to test novel systems for power generation and thermal control; also to be determined is the survivability of COTS electronic components. These goals will be achieved by taking data from the satellite systems while on orbit, and transmitting it to ground stations for post processing by University of Cincinnati students.

Technology Demonstration

Novel solutions to smallsat design problems, in particular:

Thermal control experiments: thermal reservoir and thermal switch.

Attitude control by reaction wheel (built in-house).

Effects of radiation on COTS electronics (flash memory).

Increased power generation using solar concentrators.

Mission Objectives

Survival of spacecraft on-orbit.

Operation of spacecraft by student team.

Data collection from experiments using student-built and operated ground station.

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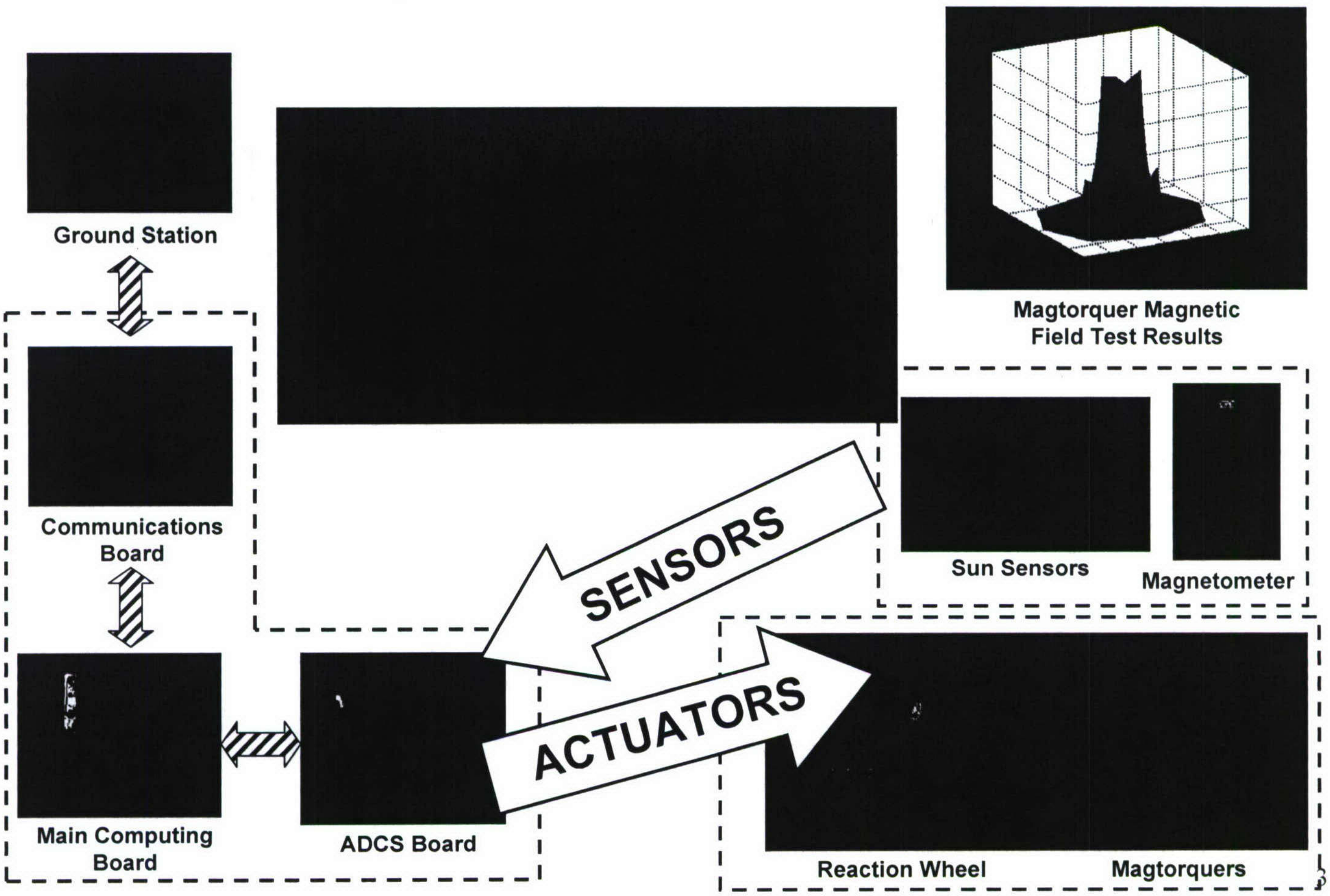
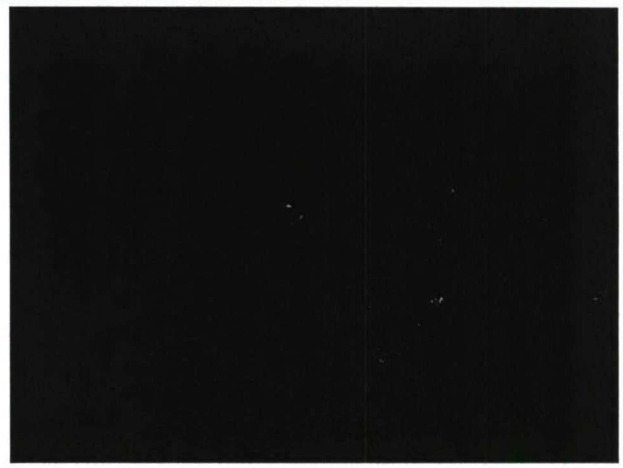
Attitude Determination and Control System (ADCS)

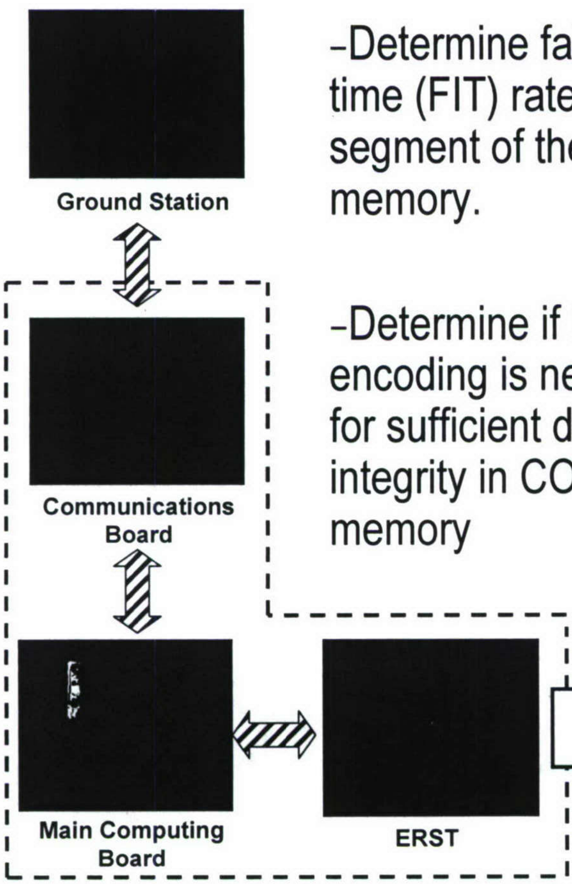


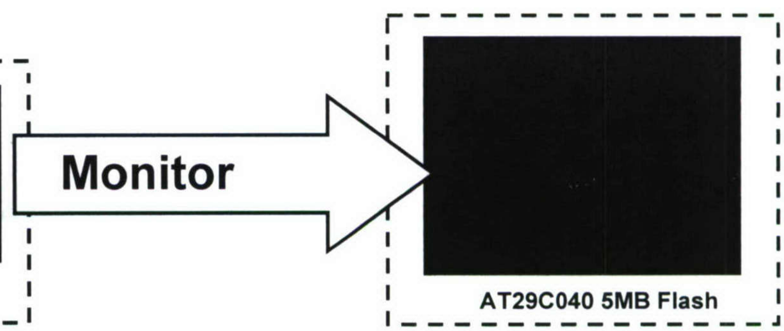
Electronics Radiation Susceptibility Test (ERST)

-Determine failures in time (FIT) rate for each segment of the flash memory.

-Determine if Hamming encoding is necessary for sufficient data integrity in COTS flash memory







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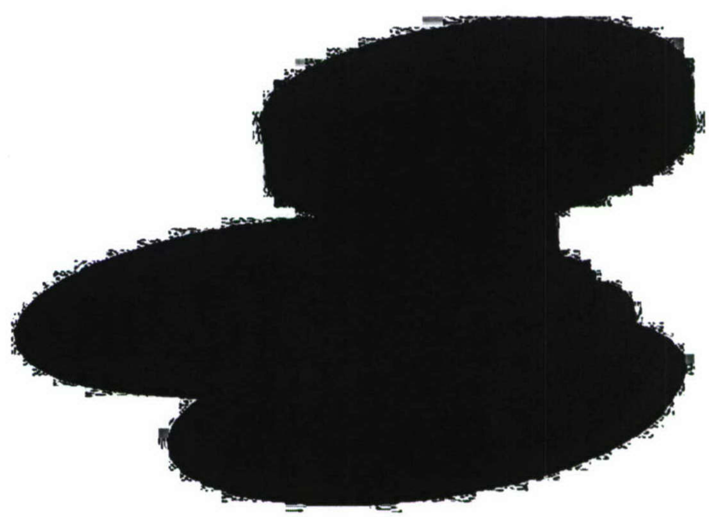
Multifunction Spacecraft Flywheel for Nanosatellites (MSFN)

- Sweat Fit Flywheel Design
- 3 1/3 FOS on Fit (Tested)
- Capable of 4300 RPM at Bus Voltage (~ 6 Minutes from 0 RPM to Steady State)
- 2.17 lbf Disturbance Force at Max RPM
- I_{zz} = 4.32 lbf*in^2



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Solar Panels

Honeycomb and Bonding

–Honeycomb: 0.50” thick sandwich with 0.020 facesheets, core is six pound density with perforated hex core

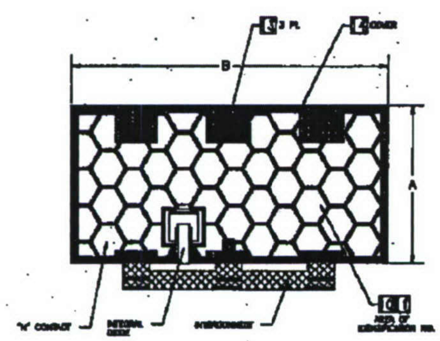
–Adhesive: FM300K Structural Adhesive Cytec Inc

–Kapton Film: 0.002”-0.003” thick film bonded with KM3002M Film Adhesive 0.75” wide

–Solder: Concorde Electronics, SN62PB36AG02 with R flux

–Primer: NuSil CF2-135

–Silicone: NuSil CV-2289, NuSil CV10-2568



Solar Cells

-Spectrolab Single Junction CIC’s

-Total voltage of 167.424

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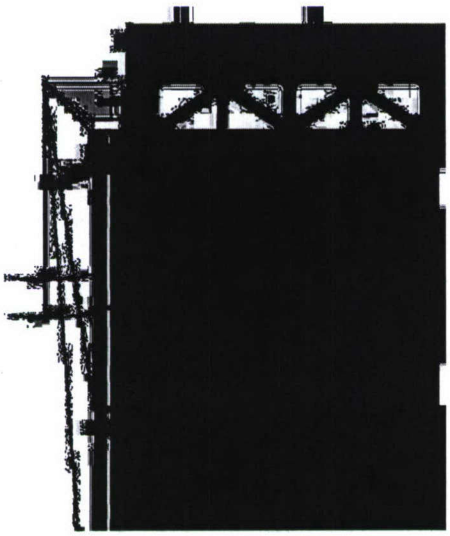
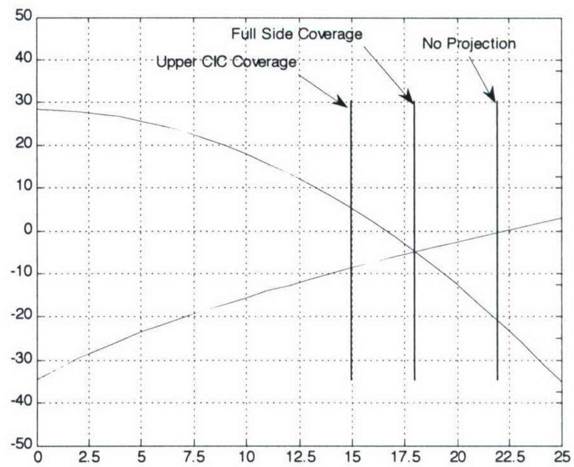
Solar Collector/Radiator for Nanosatellites (SCRN)





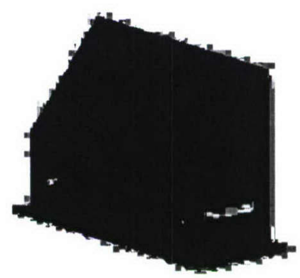
– 1x SCRN Can Produce Up to a 3% Increase in Power Generation for BEARSat

– Current SCRN Material: Acrylic, Ideal SCRN Material: Quartz

– Both Provide High Transmission Properties and Low Dispersion

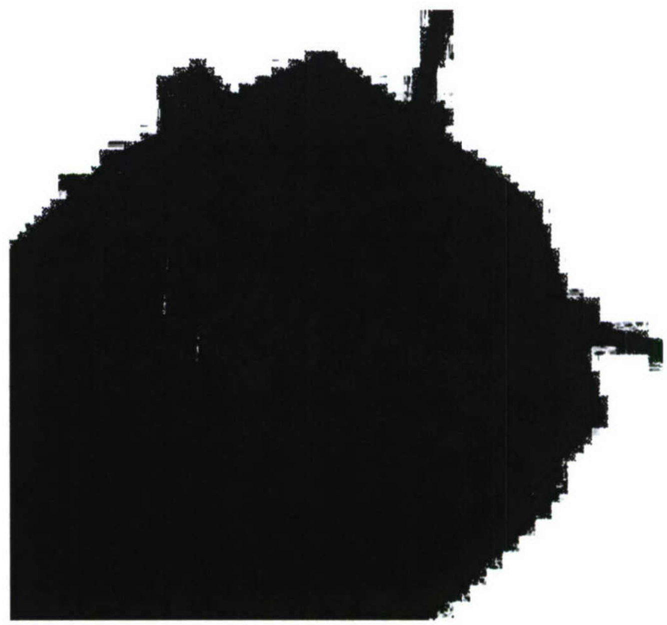
– Both have Indexes of Refraction around n=1.5

– Quartz Provides Better Durability in Extreme Conditions



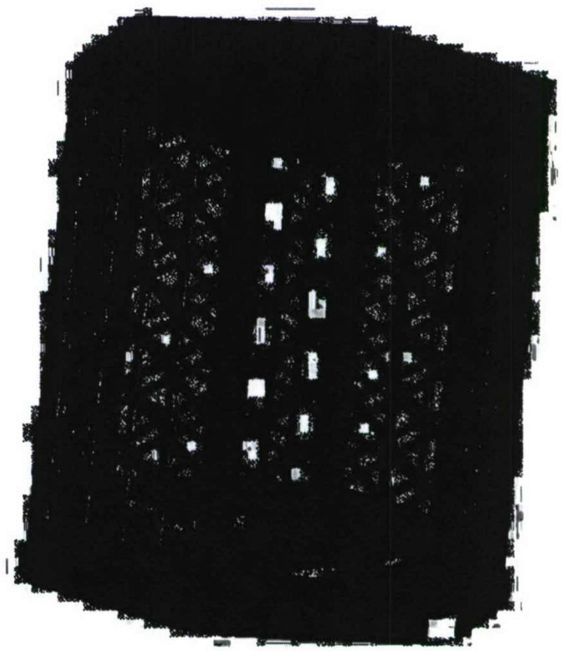
UNIVERSITY OF Cincinnati **BEARSat Antennas**

- The antennas consist of 2 crossed dipoles made of oxygen free copper strips to communicate with the satellite.
- Four N-type connectors and 50 ohm RG-58 coaxial cables are used to assemble them to the structure.



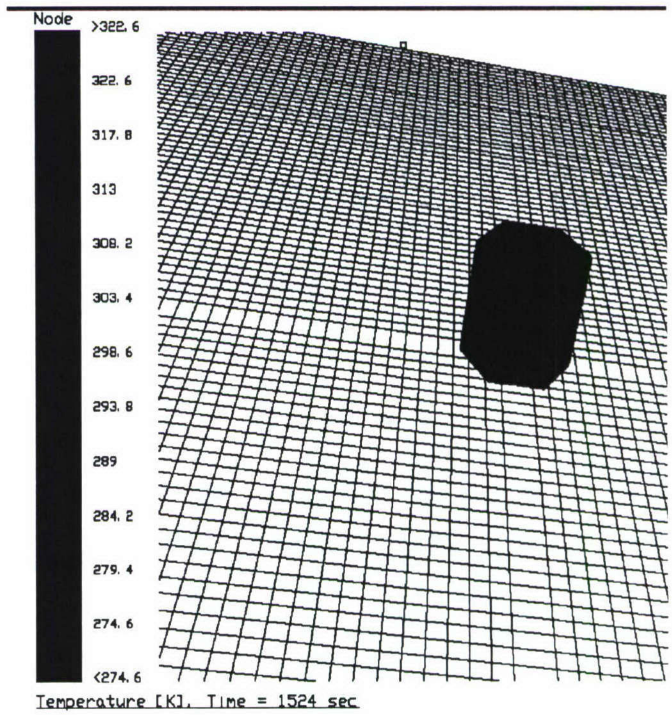
BEARSat Primary Structure

- Aluminum 6061-T6
  - Black Anodized



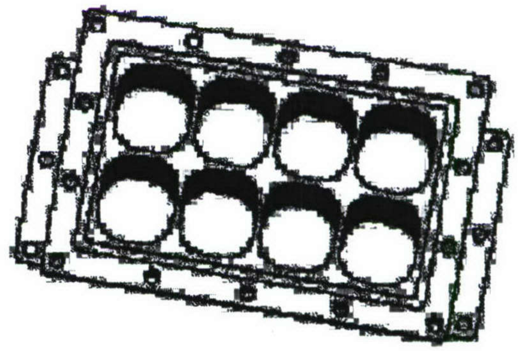
Thermal Analysis and Models

- Software
  - Cullimore and Ring Technologies
    - ThermalDesktop, RadCad Sinda/Fluint, AutoCad
- Model
  - Simplified with solid panels
  - More than 300 nodes including heat sources for powered electronics
- Orbit
  - LEO
  - 1000 km
  - 28.5 degree inclination
- Greatest Temperature Variation
  - -20 C to 58 C

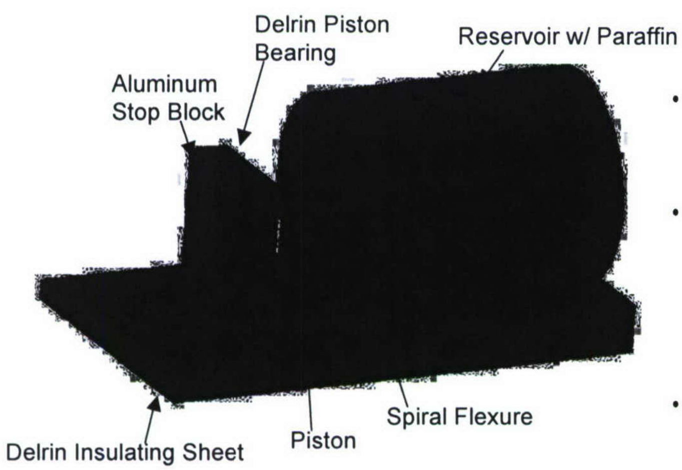


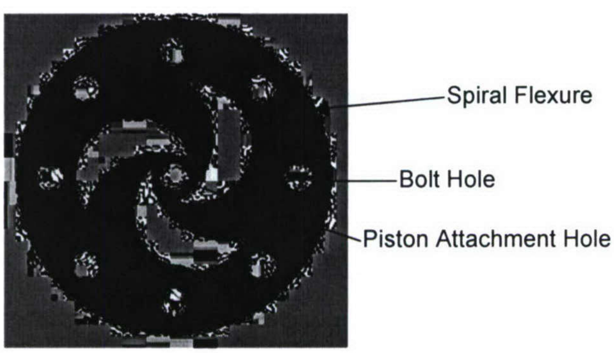
PCMR

- PCMR – Phase Change Material Reservoir
- Purpose
  - Maintain more constant temperature within satellite, especially communications box
- Background
  - Phase Change Material (Paraffin) has a melting point of ~20 C
  - Upon solidification, heat (latent heat of fusion) is given off to surrounding
  - Upon melting, heat is absorbed into paraffin
- Reasoning
  - This allows the paraffin to act as a heat storage system
    - When excess heat is not needed, the paraffin will absorb it from the system
    - When more heat is needed, the paraffin will release it to the system
  - Allows the satellite to maintain a constant desired temperature around 20 C



Phase Change Material Switch (PCMS)





- Passive Thermal Control Experiment
  - Paraffin expands as heated, pushing out a piston to create a thermal path
- Successful Prototype Test
  - 4mm extension from frozen to fully expanded
  - Designed flexure allowed piston retraction
  - Space rated elastomer successfully contained paraffin
- In-orbit operation
  - Delrin sheet thermally isolates PCMS from the battery box
  - Kapton heaters and a thermoelectric cooler will allow a controlled experiment
  - Thermocouple embedded in the stop block will track temperature changes, allowing detection of thermal path creation

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BEARSat Power System

- Power generation: Spectrolab single junction solar cell array
- Power storage: 10 Sanyo N4000DRL NiCd batteries (2 sets of 5 in parallel)
- Power delivery: Power board regulation and distribution on 5V and 12 V

Subsystem Nominal Usage

Subsystem	Power (W)
Power Control	1.14
C&DH	0.93
ADCS	1.98
Comm	3.47
ERST	0.51
Total	8.30
With 15% margin	9.55

Battery Depth of Discharge: 32%

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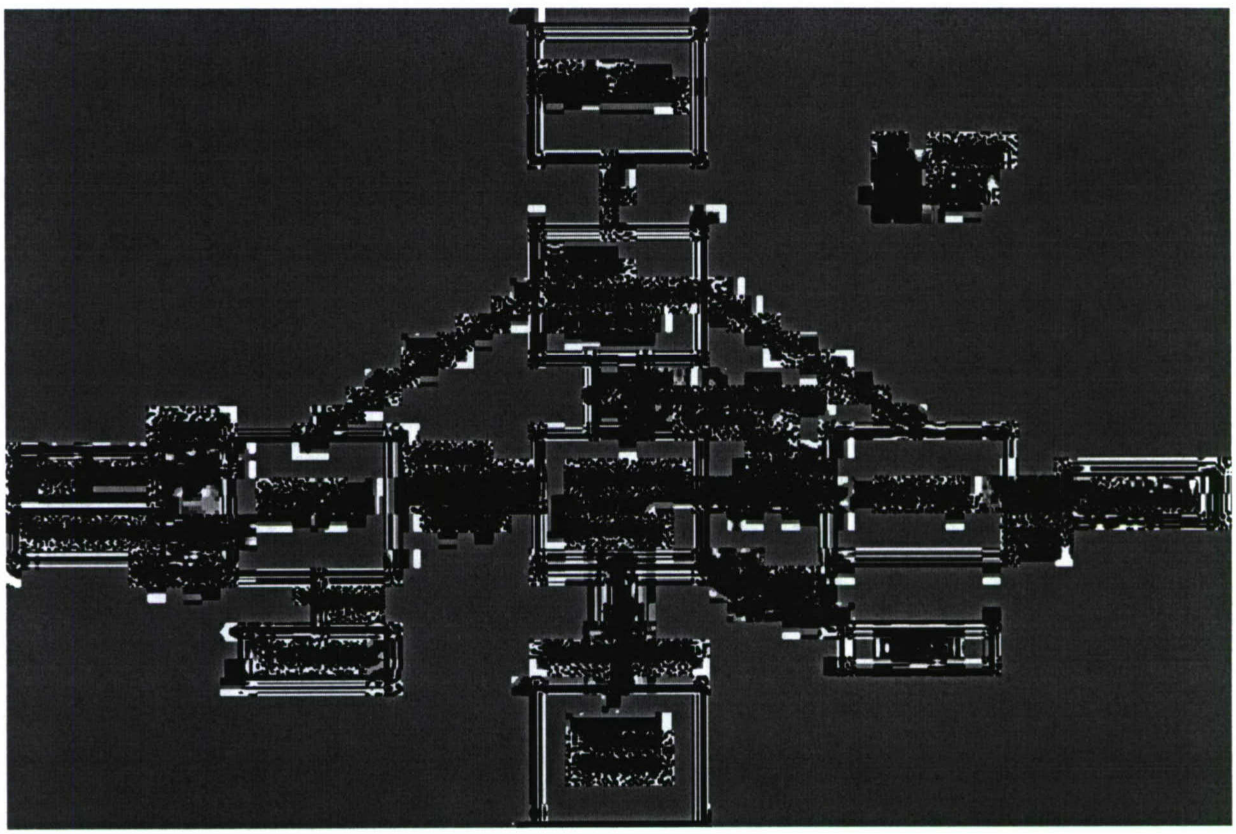
Power Regulation Overview

[redacted]

System Overview



Graphic System Overview

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